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Experimental investigation of climatic effects on the efficiency of a solar chimney pilot power plant

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ABSTRACT

Without any shadow of doubt, energy production based on renewable energies is one of most fundamental methods for energy generation for the near future. Solar chimney power plant is a relative novel technology for electricity production from solar energy. In this stud, after designing and making a solar chimney pilot power plant with 10 m collector diameter and 12 m chimney height, the temperatures and air velocities were measured. The temperature and velocity readings were carried out for some specified places of collector and chimney with varying some parameters on different days. Because of green house effect happened under the collector, the temperature difference between collector exit and the ambient reached to 25 °C, and this phenomena caused creation of air flow from collector to chimney. The air inversion at the bottom of the chimney was observed after sunrise, on both cold and hot days. The air inversion appears with increasing solar radiation from a minimum point and after a while, it is broken by the collector warm-up. After the inversion breaking, there would be a steady air flow inside the chimney. The maximum air velocity of 3 m/s was recorded inside the chimney, while the collector entrance velocity was zero.

1. Introduction

The concept of solar chimney power technology was first conceived in 1931 by a German author, Hanns Gunther. The technology combines three components: a collector, a chimney and turbines [1]. In the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground, and then a large body of air heated by the absorber, rises up the chimney, due to the density difference of air between the chimney base and the surroundings. The rising air drives large turbines installed at the chimney base to generate electricity. In 1978, the concept was proven with the operation of a pilot 50 kW power plant in Manzanares, Spain [2].

As the solar chimney power plant systems could make significant contributions to the energy supplies of those countries where there is plenty of desert land, which is not being utilized, and sunlight available in Africa, Asia and Oceania, researchers have made many reports on this technology in the recent few decades [3]. In the recent years, more and more researchers have shown strong interest in studying such solar thermal power generating technology for its huge potential of applications all over the world. Four pilot solar chimney power models were in succession built by Krisst [4], demonstrated a "backyard-type" device with a power output of 10 W in West Hartford, Connecticut, USA. Kulunk [5] produced a micro scale electric power plant of 0.14 W in Izmit, Turkey. Pasumarthi and Sherif [6] developed a mathematical model to study the effect of various environmental conditions and geometry on the air temperature, air velocity, and power output of the solar chimney. They also developed three models of solar chimneys in Florida and reported the experimental data to assess the viability of the solar chimney concept [7].

The researchers also carried out experimental investigations on the performances of the models [6]. More theoretical investigation and simulations have been carried out by Padki and Sherif [8], by developing a simple model to analyze the performance of the solar chimney. Lodhi [9] presented a comprehensive analysis of the chimney effect, power production, efficiency, and estimated the cost of the solar chimney power plant set up in developing nations. Bernardes et al. [10] presented a theoretical analysis of a solar chimney, operating on natural laminar convection in steady state. Gannon and Backström [11] presented an air standard cycle analysis of the solar chimney power plant for the calculation of limiting performance, efficiency, and the relationship between the main variables including chimney friction, system, turbine, and exit kinetic energy losses. They also presented an experimental investigation of the performance of a turbine for the solar chimney systems; the measured results showed that the solar chimney turbine presented has a total-to-total efficiency of 85–90% and a total-to-static efficiency of 77–80% over the design range [12].

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Table 1
Properties of polycarbonate.

Average value	Property	Average value	Property
100 (N/mm^2)	Flexural strength	850 (J/m)	Impact strength
2400 (MPa)	Modulus of elasticity	88 (%)	Light transmission
≥65 (MPa)	Tensile stress at break	1.2 (g/cm^3)	Specific gravity
>100 (%)	Elongation at break	0.065 (mm/m °C)	Coefficient of thermal expansion
1.17 (kJ/kg K)	Specific heat	−40 °C to +120 °C	Working temperature
140 (°C)	Heat deflection temperature	2.3–3.9 (W/m^2 °C)	Heat conductivity
20 db	Effect of soundproof (10 mm hollow): decay	≥60 (N/mm^2)	Tensile strength

Later, Backström and Gannon presented analytical equations in terms of turbine flow and load coefficient and degree of reaction, to express the influence of each coefficient on turbine efficiency [13]. Bernardes et al. [14] developed a comprehensive thermal and technical analysis to estimate the power output and examine the effect of various ambient conditions and structural dimensions on the power output. Pastohr et al. [15] carried out a numerical simulation to improve the description of the operation mode and efficiency by coupling all parts of the solar chimney power plant including the ground, collector, chimney, and turbine. Schlaich et al. [16] presented theory, practical experience, and economy of solar chimney power plant to give a guide for the design of 200 MW commercial solar chimney power plant systems. Ming et al. [17] presented a thermodynamic analysis of the solar chimney power plant and advanced energy utilization degree to analyze the performance of the system, which can produce electricity day and night. Liu et al. [18] carried out a numerical simulation for the MW-graded solar chimney power plant, presenting the influences of pressure drop across the turbine on the draft and the power output of the system.

Bilgen and Rheault [19] designed a solar chimney system for power production at high latitudes and evaluated its performance. Pretorius and Kröger [20], Ninic [21], Onyango and Ochieng [22] evaluated the influence of a developed convective heat transfer equation, more accurate turbine inlet loss coefficient, quality of collector roof glass, and various types of soil on the performance of a large scale solar chimney power plant [23]. A program, to construct a 100 MW solar chimney power plant in a desert, in Rajasthan, India, was scheduled, but then was aborted owing to the potential danger of nuclear competition between India and Pakistan [24]. Recently, the Australian government decided to support a proposed 50 MW demonstration plant with a chimney about 480 m tall at Tapio Station [25].

2. Solar chimney set-up

For performing the experimental works and temperature measuring, a solar chimney in pilot scale was built in University of Zanjan, Iran, in 2010. The chimney height is 12 m and the collector has 10 m diameter. The collector slope angle must have been designed so that it could absorb the maximum solar radiation [26]. Zanjan town has geographical length and width of 48.45 and 36.68, respectively [27]. So, for absorbing the most heat by collector, the collector exit must have a height of 5tan $\pi/6$. Due to design limitations, the exit was built with 1 m height and the collector inlet was built with 15 cm height. Because of heat resistance and low price of polyethylene (PE), a 12 m PE pipe with diameter of 25 cm was used for making the chimney. The friction is low in the pipe, due to low diameter and low height. For strengthening the structure, 48 pieces of 4 * 4 steel profiles were used in the collector and the collector bases were put inside concrete. For preparing a proper green house effect, polycarbonate (PC) sheets were applied for making the collector sheets. Polycarbonate sheets are mechanically strong, transparent, tough, heat resistant, and fairly UV resistant. For preventing heat loss and increasing the green house effect, two-layered

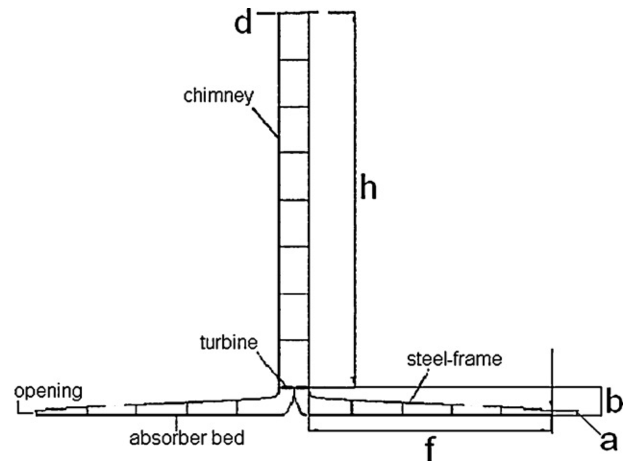

Fig. 1. Schematic of the chimney.

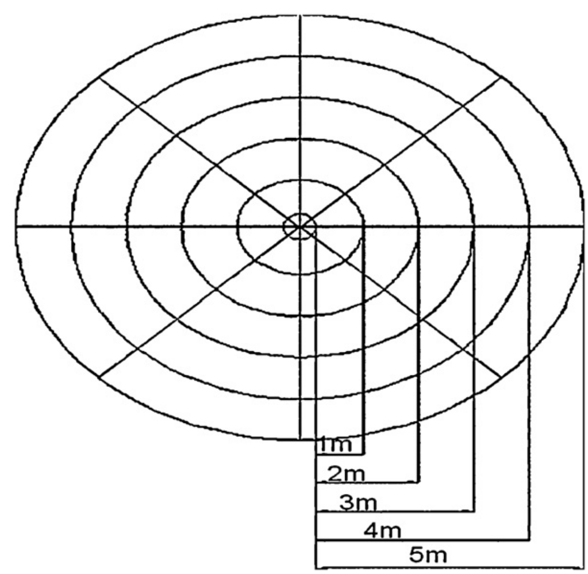

Fig. 2. Schematic of the collector structure.

PC sheets were selected. The typical properties of PC are shown in Table 1.[1] Since black material can be more thermally black [28], the ground under collector was totally covered by black films of polyethylene. The films are able to absorb more radiation waves for the maximum radiation-stored heat conversion. For decreasing the collector heat loss, the sheets were put on the collector so that cover all the structure. Schematics of the chimney and the collector structure are shown in Figs. 1 and 2, respectively. The size

[1] http://www.frenchporte.com/sheet.html.

Table 2
Size of chimney different parts.

Parameter	Figure index	Size
Height of collector inlet	a	15 cm
Height of collector exit	b	1 m
Chimney diameter	d	25 cm
Collector radius	f	5 m
Chimney height	h	12 m

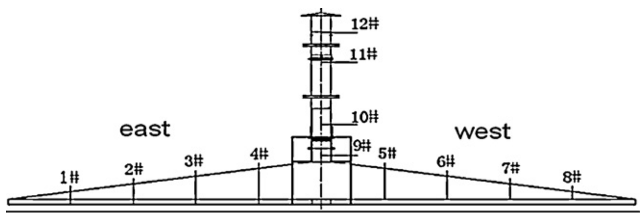

Fig. 3. The chimney sensor lay-out.

Fig. 4. A photo of solar chimney.

of different parts is shown in Table 2. For purpose of temperature measuring, SMT-160 sensors were used and all data were recorded in a data-logger. Totally, 12 temperature sensors were used, which of 4 sensors were installed inside the chimney and 8 others were located in the collector. The chimney sensors have 3 m distance and the distances of collector sensors are shown in Fig. 3.

For measuring of ambient temperature measurement, resistance sensors which were put 2 m over ground were used and the outside wind velocity was measured by a précised wind speedometer which was put 10 m over ground. For purpose of measuring air flow velocity inside the chimney, the anemometer model AVM-702 was utilized. The speedometer propeller was located at the chimney entrance and the velocities were recorded successively by the data-logger. Photo of the made chimney set-up is shown in Figs. 4 and 5 demonstrates the collector inside and the black plastic films which are hammered onto ground.

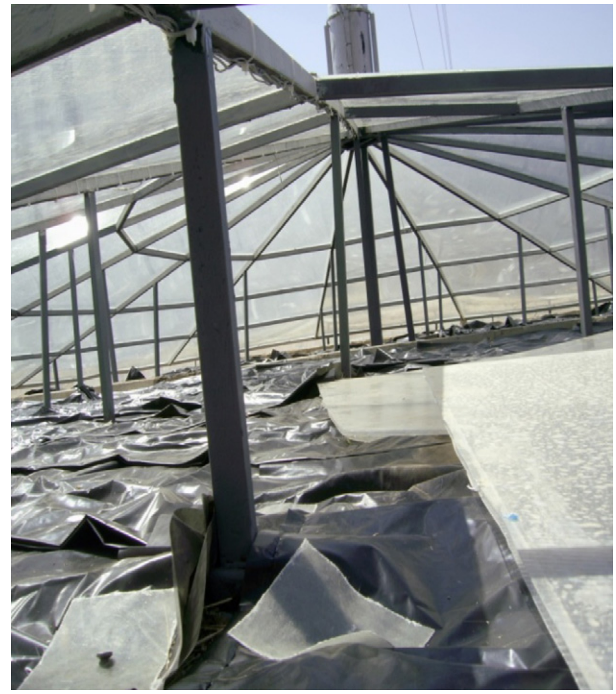

Fig. 5. Photo of collector inside.

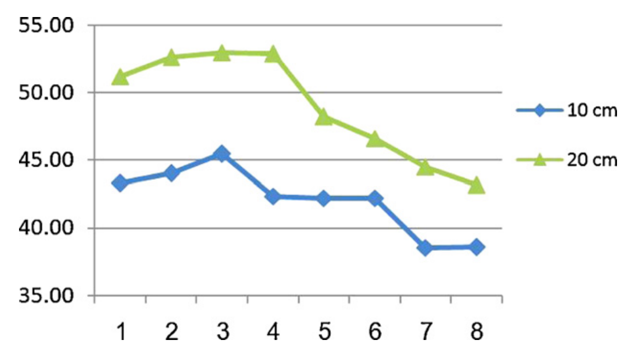

Fig. 6. Temperature changes of collector for different height on a warm day (ambient temperature: 30.5 °C, chimney air velocity: 2.66 m/s).

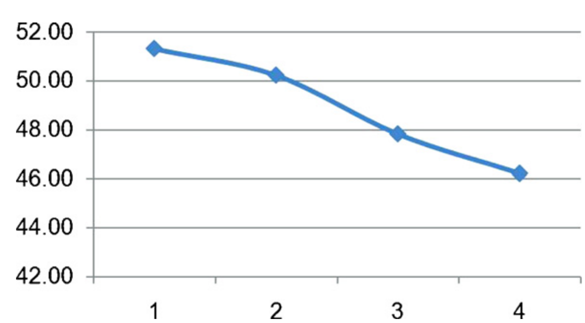

Fig. 7. Temperature changes at different heights of chimney on a warm day (ambient temperature: 30.5 °C, chimney air velocity: 2.66 m/s).

3. Results and discussion

3.1. Temperature changes

The temperature changes were obtained at 2:30 p.m. on 16th of September, 2010. The collector temperatures at two levels of height and the chimney temperatures versus different height are presented in Figs. 6 and 7, respectively. Fig. 6 shows the tempera-

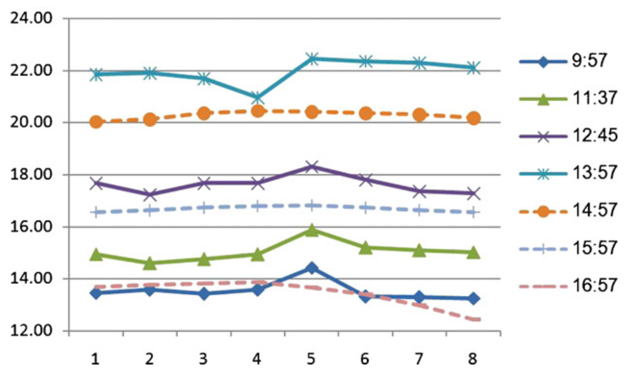

Fig. 8. Temperature changes of collector for different height on a cold day (ambient temperature: 12 °C, chimney air velocity: 1.37 m/s).

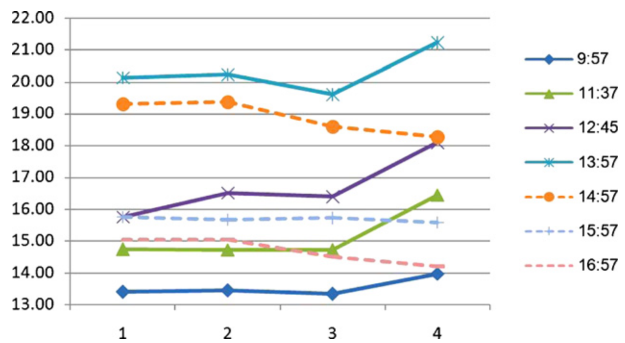

Fig. 9. Temperature changes at different heights of chimney on a cold day (ambient temperature: 12 °C, chimney air velocity: 1.37 m/s).

ture changes at two height levels, which of one is near the ground and another one is near the collector. According to this figure, the following results can be obtained:

1. The temperatures shown by the eastern sensors are higher than of the western part of the collector. The reason is that the data were obtained in a windy day and the wind direction was west to east. Although, a 0.5 m high wall all around the collector inlet neutralizes the outside air velocity but, the collision of the air on the collector west side causes the temperature decrease.
2. The temperature under the collector warms up, due to the air displacement. The solar warmth is first absorbed by ground and then the air moving on the surface, absorbs the heat and carries to the upper layers. Therefore, the temperature decreases by furthering from ground and approaching to the collector ceiling. This can be observed of Fig. 6 that the temperature near the ceiling is lower than of the ground.
3. The air temperature has the maximum reading at the center and the lowest temperature is related to the inlet.
4. The temperature difference between the ambient (2:30 p.m. on 16th of September, 2010) and point 9 (1 m above ground, at the center of chimney) is 21.5 °C and that is enough for creating air movement driving force.
5. The chimney temperature decreases by increasing chimney height, this is due to the convection heat transfer of the outside colder weather.

3.2. Daily changes for a cold day

The temperatures of different zones on a cold day (26th of October) were logged between 9:57 a.m. and 4:57 p.m. and the results are depicted in Figs. 8 and 9. During an ordinary day, the collector and chimney temperature have been raised by sunrise and it has reached to a maximum amount at 1:57 p.m., after that, the temperatures have been decreased by abating the radiation power. Before sunrise, the absorber surface almost emits all the heat stored on the previous day. The surface warms up after appearing sun and its temperature raises. In afternoon, taking in account that the radiation is weak, the absorber surface absorbs a big deal of heat and rejects it via convection heat transfer. The result of this mechanism is the continuous temperature decrease. According to Fig. 9, generally in a cold day, the temperature inversion happens in morning and just at the chimney end and the inversion disappears.

According to Fig. 8, before sunrise, the air temperature inside the made pilot is nearly close to the ambient temperature. After sunrise, the absorber absorbs and stores the radiation energy and of course its temperature is low at the beginning. So, because of low temperature and heat transfer via the collector and chimney wall, the air hardly flows inside the system and this mechanism makes just a low driving force. The small air driving force will decrease along the chimney with air moving up and it feeds back to the backside of the chimney. Most of the flow movement energy is lost from the wall side toward the chimney inside, because of warming up the backside air. Therefore, the air inside the back of chimney is successfully warmed up as the form of temperature inversion, due to lost of the air upward movement energy. As it depicted in Fig. 9, its temperature is 1–3 °C higher than the temperature of point 3. When the temperature of the air inside the collector reaches near to its maximum level, the adequate driving force forms for breaking the inversion. After that, air is heated continuously by convection, and a natural fluid flow moves from the open side the collector to the chimney exit.

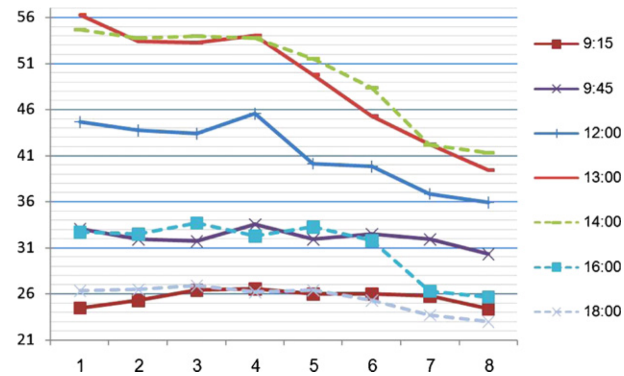

Fig. 10. Temperature changes of collector at different daily hours on a warm day (ambient temperature: 34 °C, chimney air maximum velocity: 2.9 m/s).

3.3. Daily changes for a warm day

The temperatures of different zones on a warm day (16th of September) were logged between 9:00 a.m. and 4:00 p.m. and the results are depicted in Figs. 10 and 11. As it is observed, due to radiation raise, the temperature inversion has lower presence and the inversion has been disappeared much earlier than the cold day. This, states that the more powerful radiation in summer causes quicker absorber warming up.

3.4. Air temperature per different collector inlet size

On two consecutive days with the same climatic conditions (T = 25 °C, sunny, with no wind) and at the same hour (3:30 p.m.), the temperatures of chimney different zones were read with changing the collector inlet height. The tests were done for two height size of 5 cm and 15 cm of collector inlet. The results are shown in Fig. 12. According to Fig. 12, the following results may be reported:

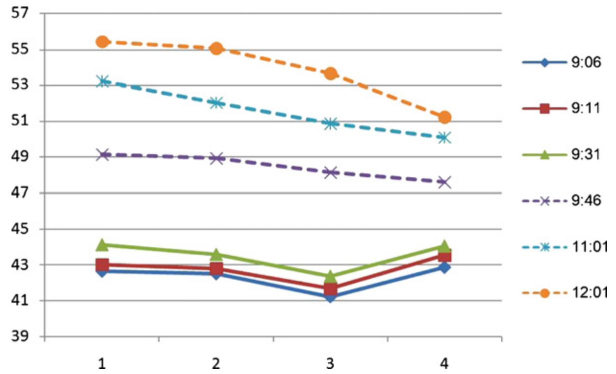

Fig. 11. Temperature changes of chimney at different daily hours on a warm day (ambient average temperature: 34 °C, chimney air maximum velocity: 2.9 m/s).

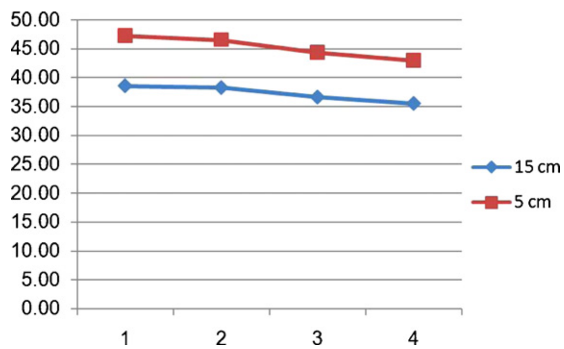

Fig. 12. Temperature changes of chimney at different collector inlet height size on two similar warm days (ambient temperature: 25 °C, chimney air velocity for 5 cm inlet: 2.78 m/s, chimney air velocity for 15 cm inlet: 2.33 m/s).

1. In none of the two cases, temperature inversion was observed. It shows that the inversion is related to the temperature and is not dependent on the geometrical parameters. Of course, other physical properties, and material properties and some states of design might cause increasing or decreasing the inversion phenomena.
2. The temperature level for the first state (5 cm) is higher than the second state (15 cm). The justification is that, in the first state, wind has lower effect on the air inside the collector when the collector inlet is closed, then the chimney temperature rises.
3. The temperature difference between the ambient and the chimney inlet is 22 °C for the first state, whereas the difference amount is 14 °C for the second state. The higher temperature difference makes the higher air velocity and hence the higher power generated [29].

4. Conclusion

By designing and building a pilot plant of solar chimney in University of Zanjan, the possibility of taking different temperature, air velocity and power factors data was prepared. In the cold days, the temperature inversion phenomena appear and the inversion effects get disappeared by increasing the day temperature.

By the chimney, the maximum air velocity of 2.9 m/s was achieved, whereas the air inlet velocity at the collector inlet was around zero. The maximum chimney temperatures were achieved at the time between 1:30 p.m. and 2:30 p.m.(maximum temperature: 60 °C at ambient temperature of 34 °C). Decreasing the inlet size of collector has positive effect on the solar chimney power efficiency. The larger collectors and the higher chimneys will make more power.

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